Hybrid Energy Storage Studies Using Batteries and Ultracapacitors for Advanced Vehicles

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Double Layer Capacitors
and Similar Energy Storage Devices

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Rational for Hybridizing a Battery Pack

- Aggressive hybrid vehicle designs need high power capability AND adequate energy storage capability.
- It is difficult for currently available batteries to meet power, life/reliability, and cost targets simultaneously.
- It is difficult for currently available ultracapacitors to meet energy, reliability, and cost targets.

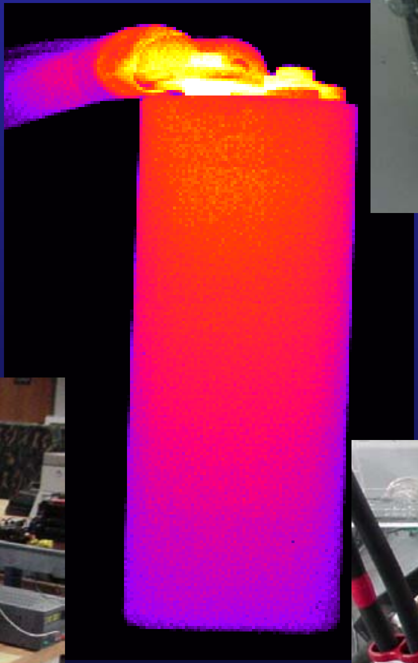
Research Objectives

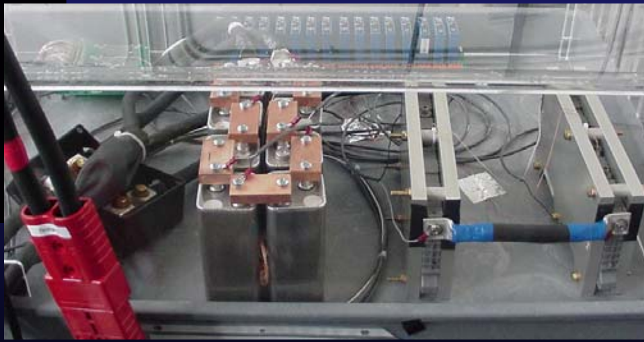
Evaluate whether hybridizing energy storage has potential for

- Satisfying technical and financial targets.
- Improving the vehicle system (mileage, performance, reliability, etc…).

Outline

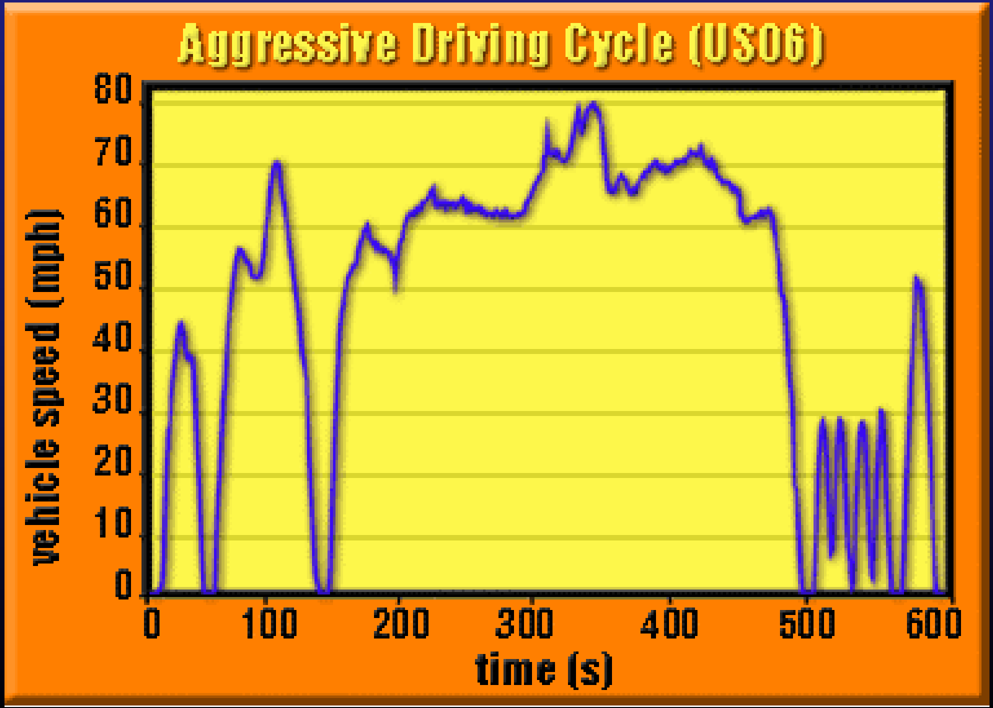
- **Exploratory Lab Tests**
- Modeling and Simulation
- Energy Storage Optimization
- Cost Analysis



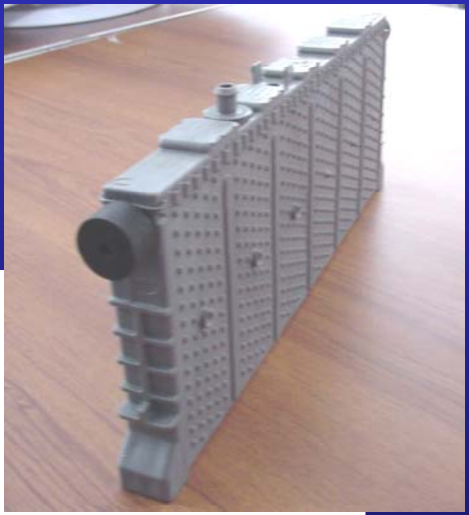


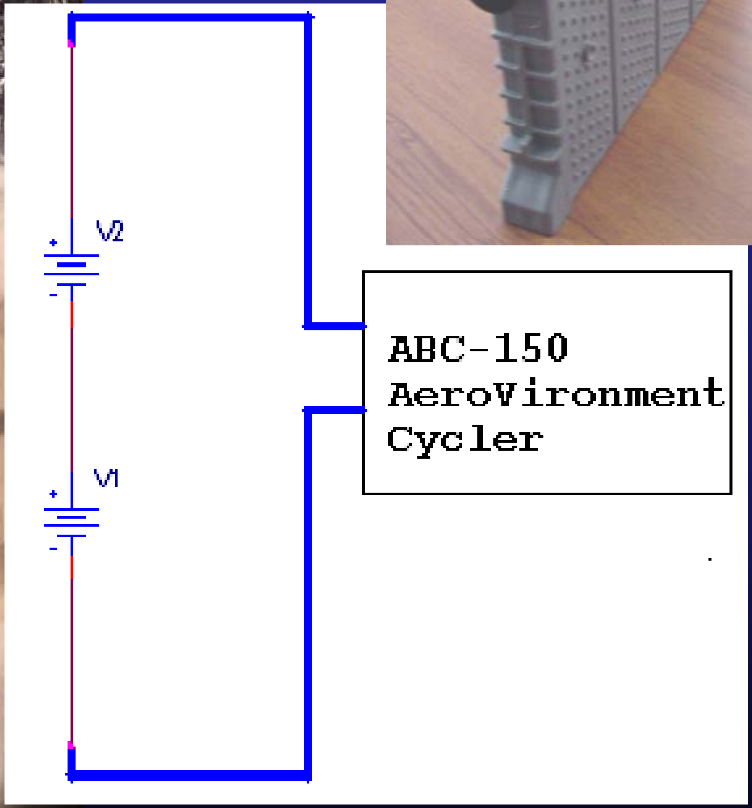
Hybridizing an Energy Storage System

- To explore the advantages and disadvantages of incorporating ultracapacitors and batteries into an HEV, we conducted laboratory tests.
- We investigated the performance over a vehicle power profile based on the EPA's US06.



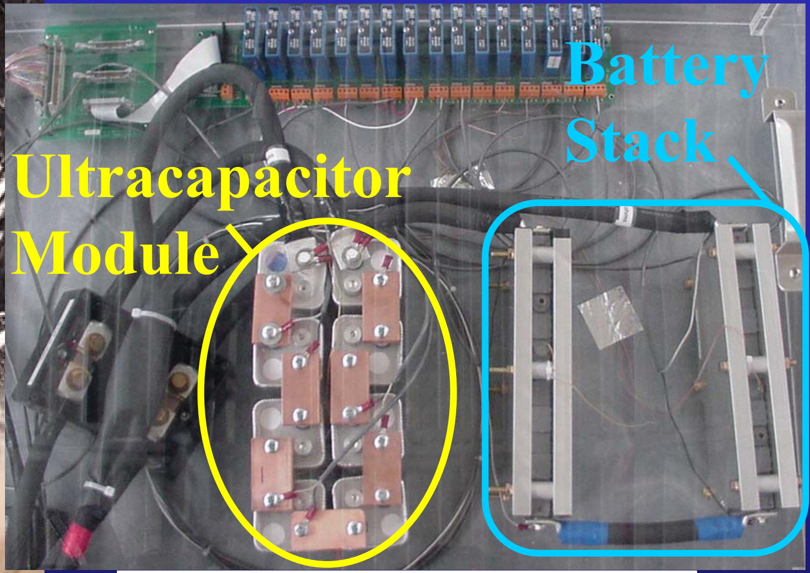
Case A – Battery-Only Pack

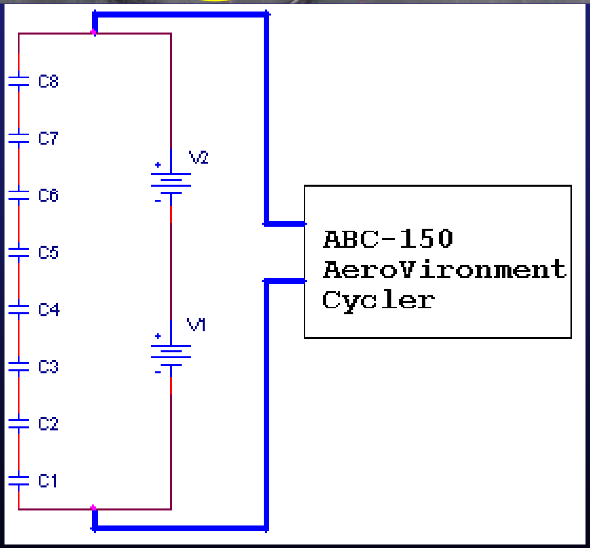




- High power NiMH batteries in the U.S. Prius
- Two 6.5Ah modules at 14.4V nominal (18V max)
- Simulated HEV power load with scaled down voltage for a US06 drive cycle

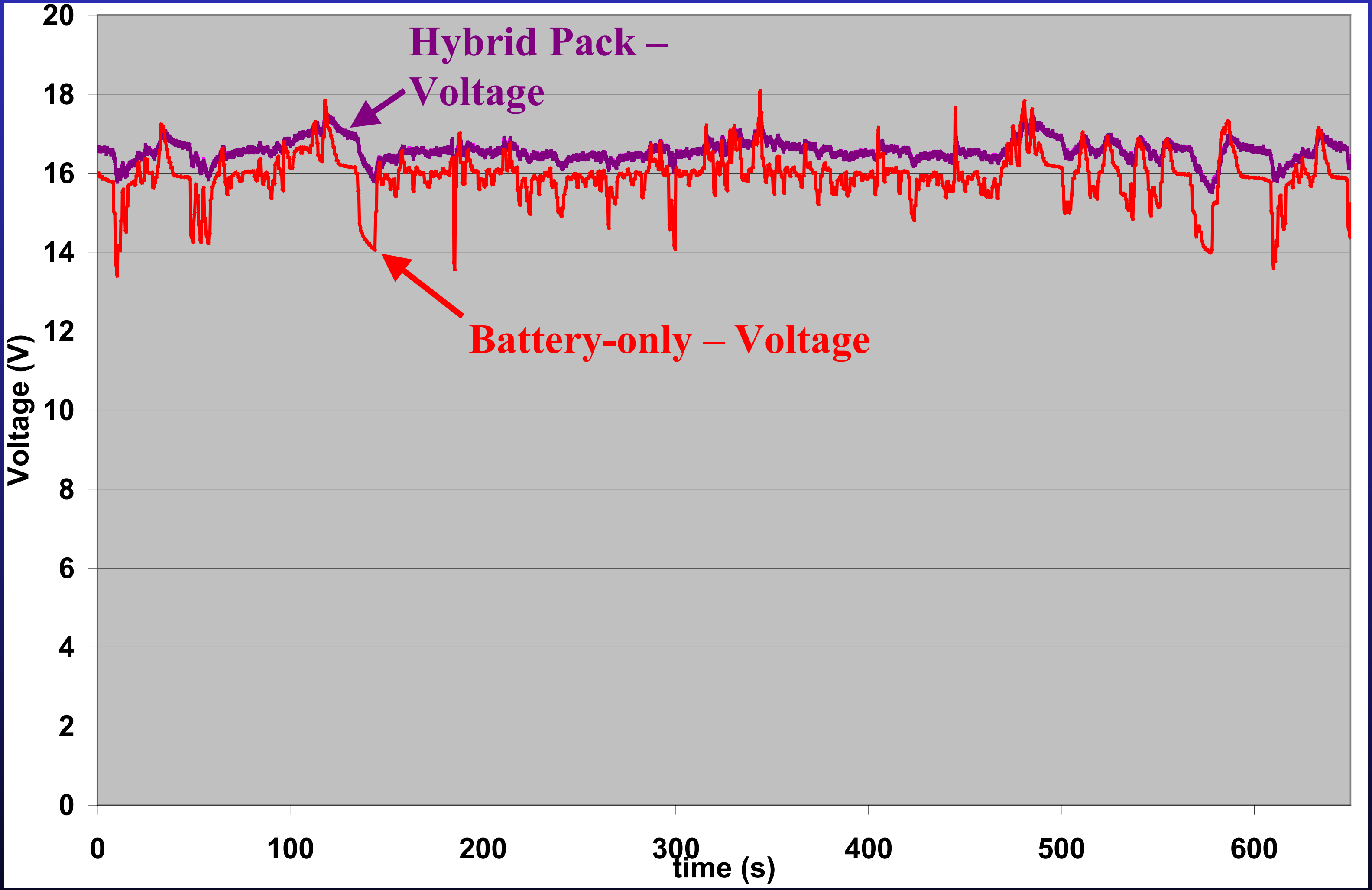
Case B - Simple Hybrid Energy Storage Pack





- Ultracapacitor module of 8 cells (up to 20V) and a 6.5Ah NiMH stack of 14.4V (18V max).
- Ultracapacitor module and battery stack are arranged in parallel to share the current load depending on internal impedance.

Ultracapacitors Filter Voltage Transients



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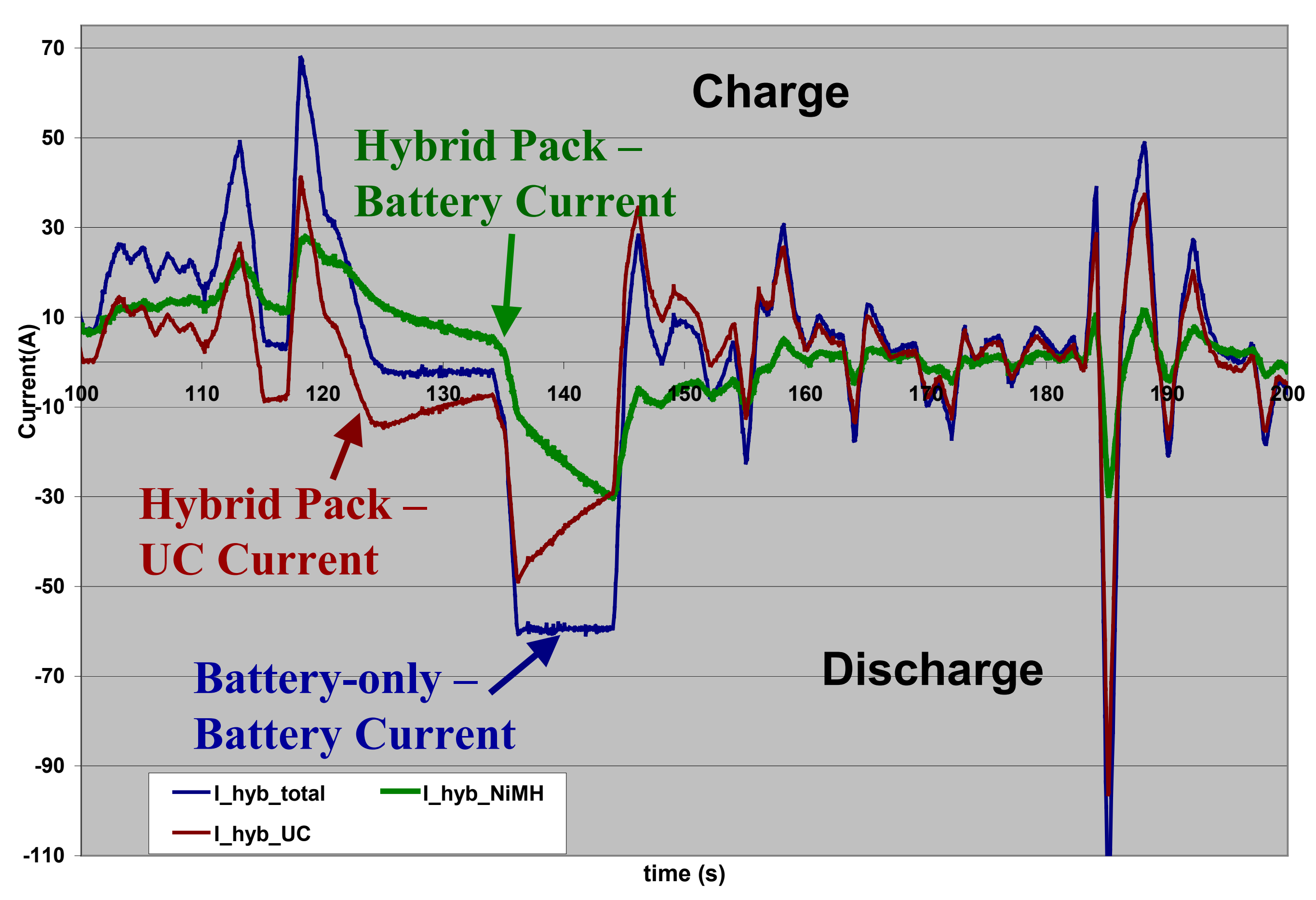
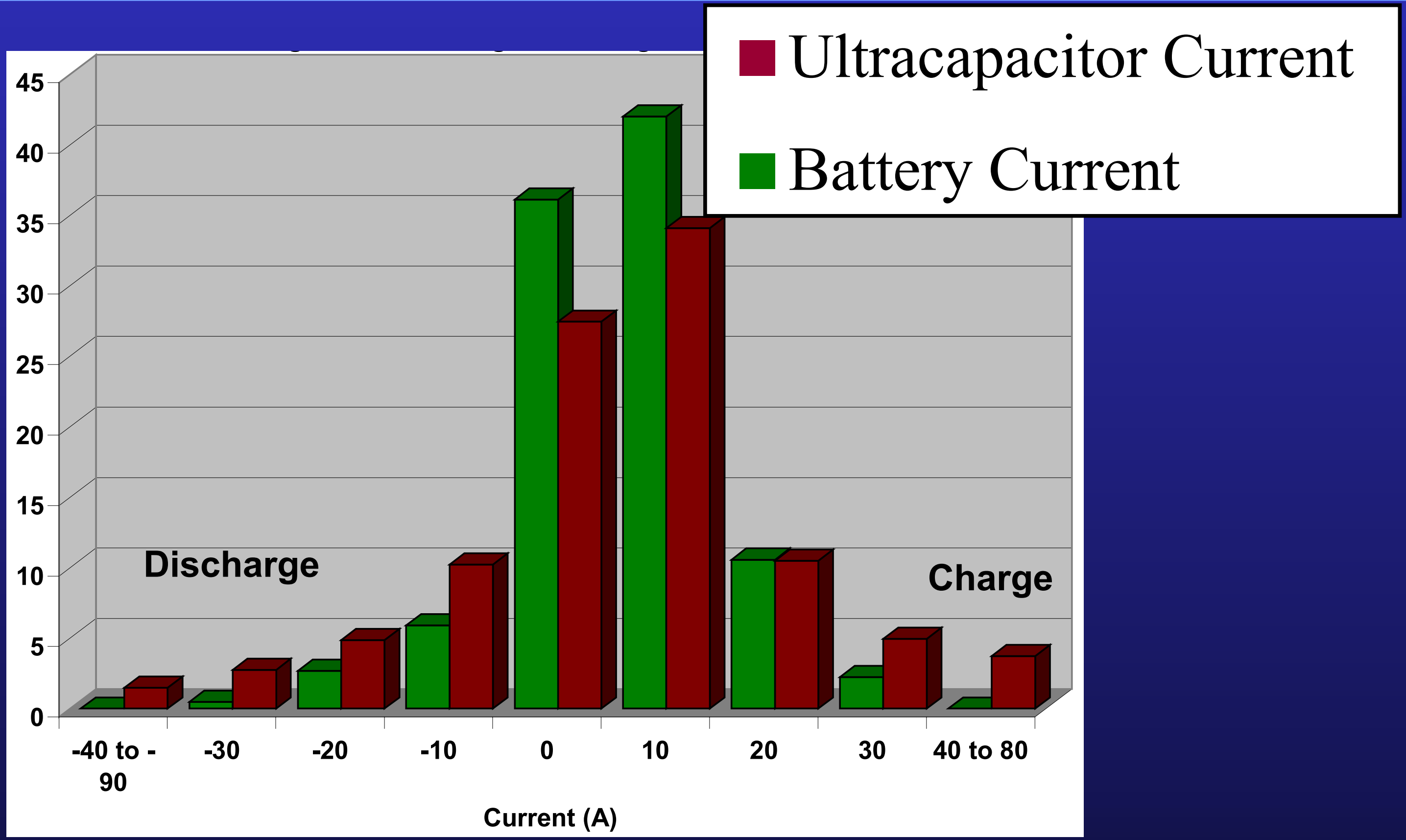
Battery Currents in the Hybrid-Pack Are Reduced Compared to the Battery-Only Pack



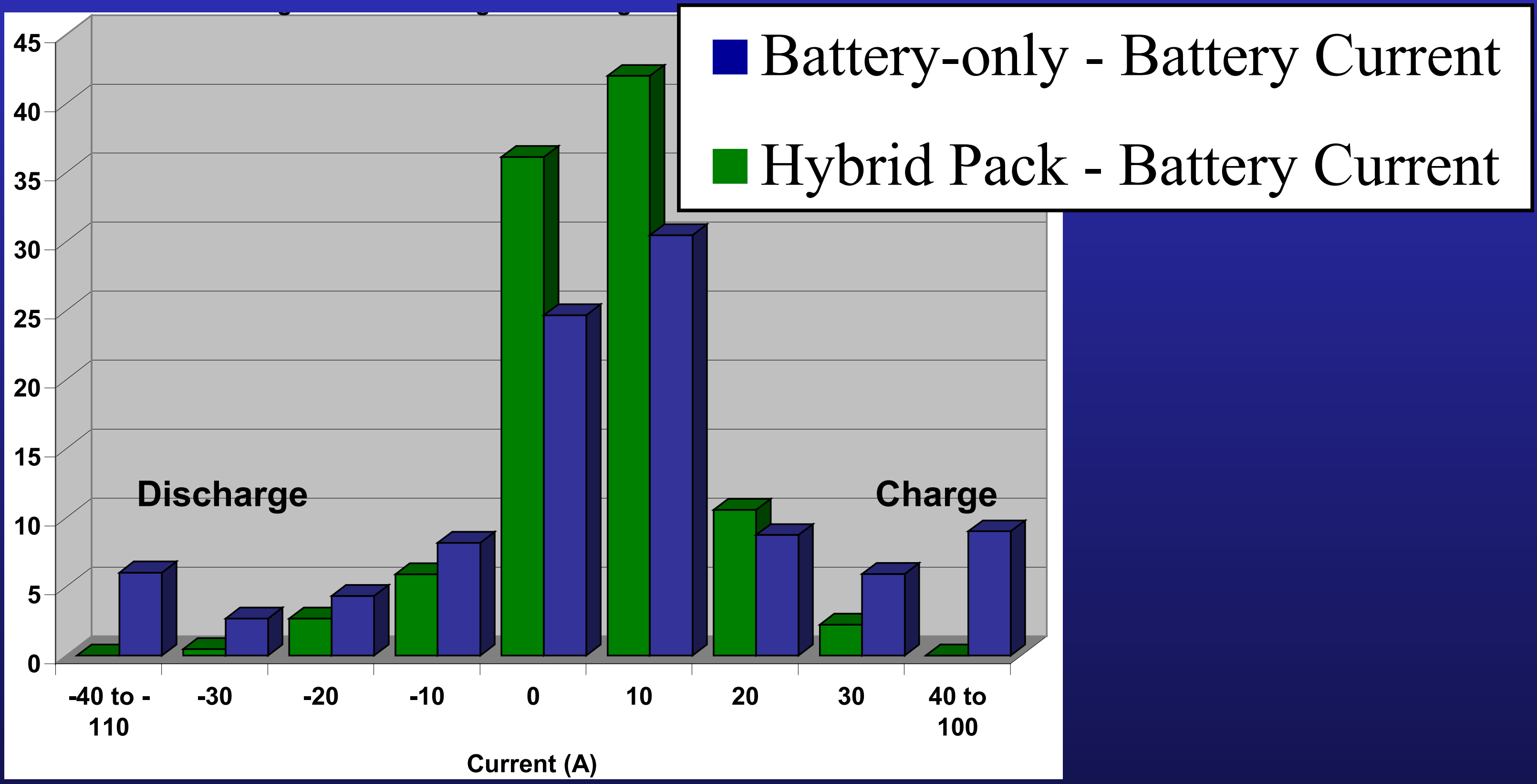
- Components in hybrid pack share currents – ultracapacitor clearly has lower impedance than high-power NiMH batteries.

Current Histogram in the Hybrid-Pack during the US06



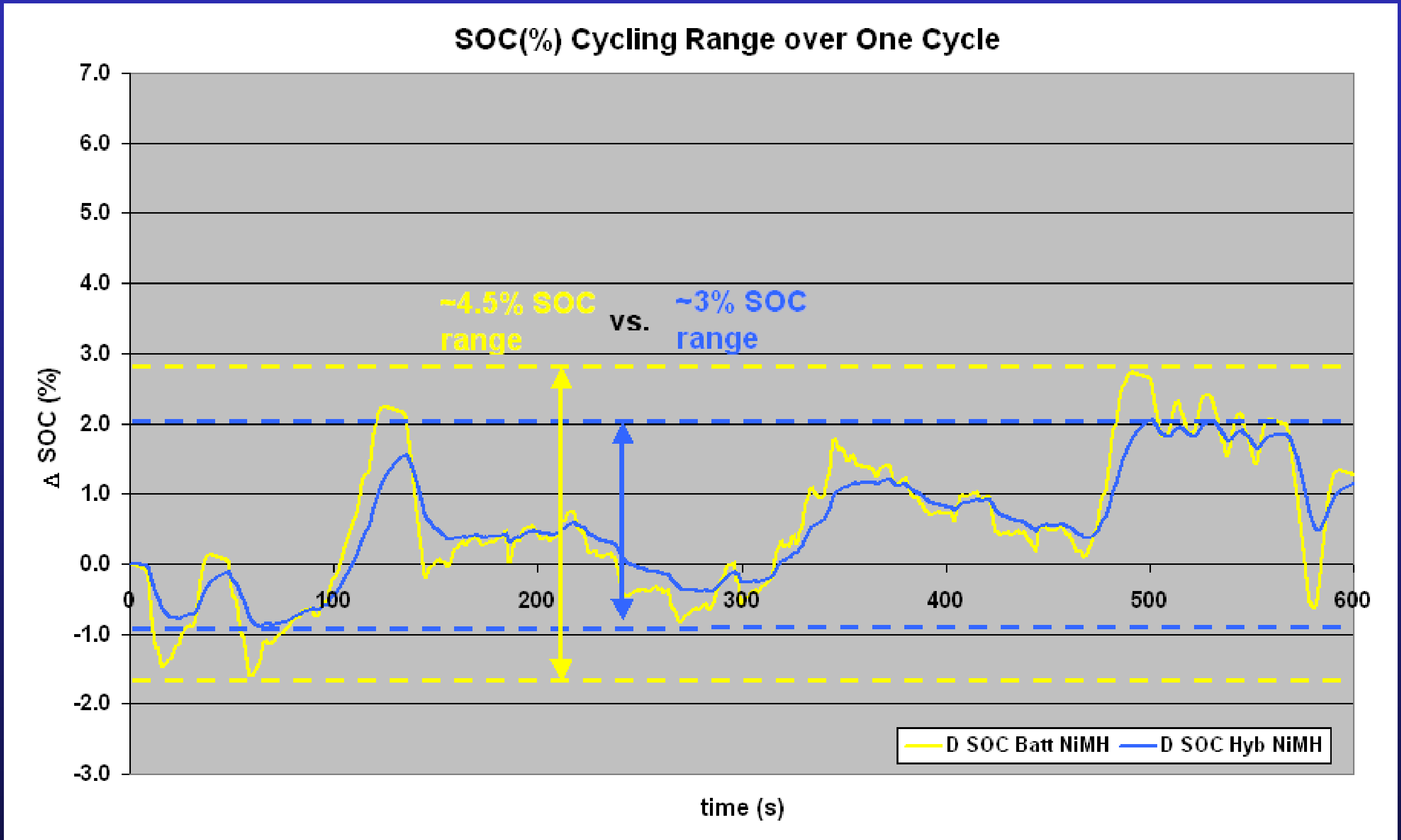
- Lower impedance UC provides all currents larger than ±40A, while the battery absorbs/supplies additional low level currents from/to the UC to correct for voltage (Ah capacity) inequalities.

Current Histogram in the Hybrid Pack and Battery-Only Pack during the US06



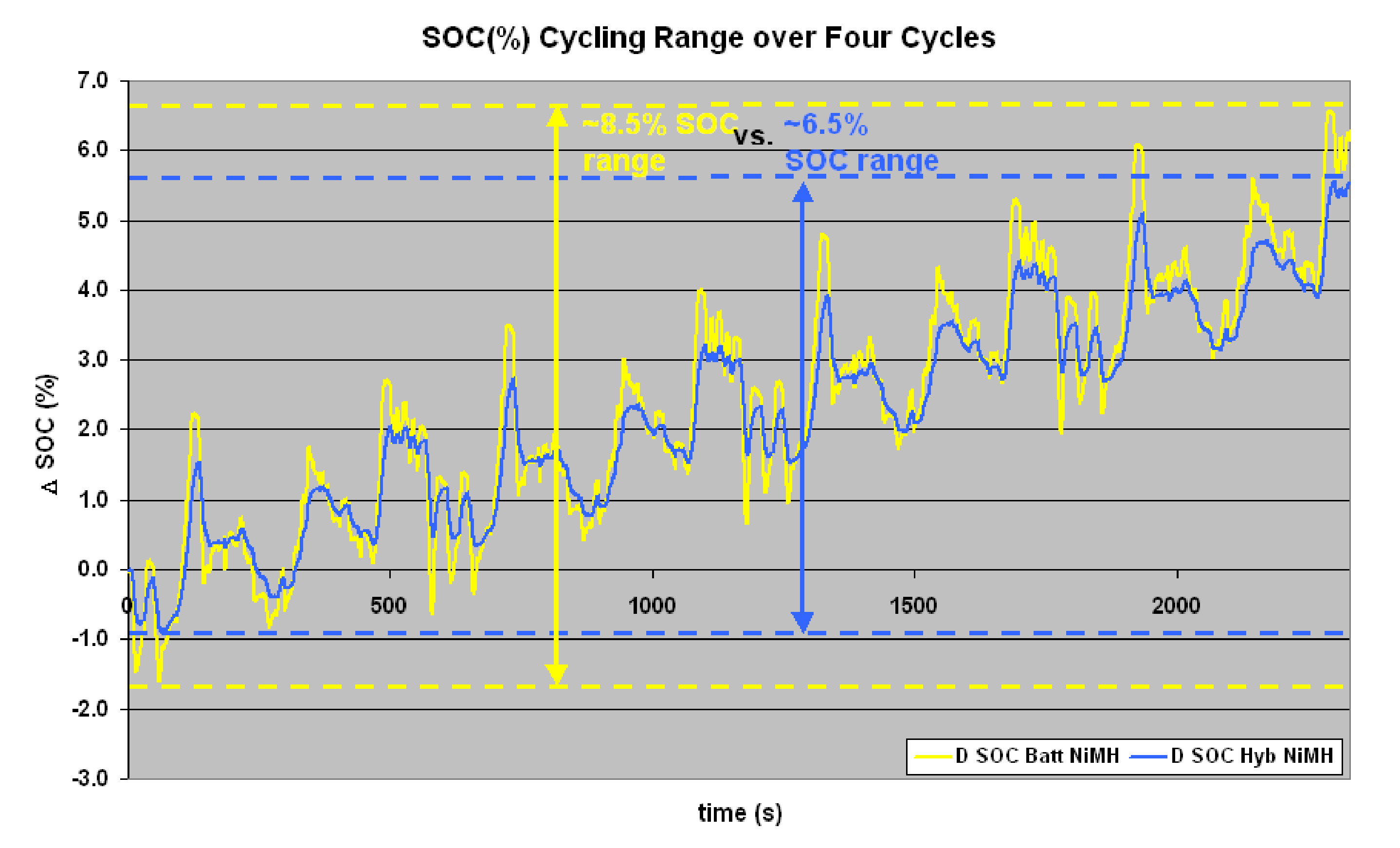
- Overall, the batteries in the hybrid pack “see” no currents larger than ±40A, while the batteries in the traditional pack see all the currents, from –110A to 100A.

33% Narrower Battery SOC Range Over the US06 Profile



- 33% narrower battery cycling range (after 10 minutes) has the potential to increase battery life.

24% Narrower Battery SOC Range Over Many US06 Profiles



- 24% narrower battery cycling range (after 40 minutes) has the potential to increase battery life.

Advantages and Disadvantages of Hybridizing Energy Storage

Advantages
- Reduced battery currents
- Reduced battery cycling range
- ↑ will have positive effect on life

Disadvantages
- Very large volume and mass
- Increased energy storage cost
- Unknown side effects of direct coupling

Hybridizing has benefits, but we need to work on drawbacks

Outline

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- **Modeling and Simulation**
- Energy Storage Optimization
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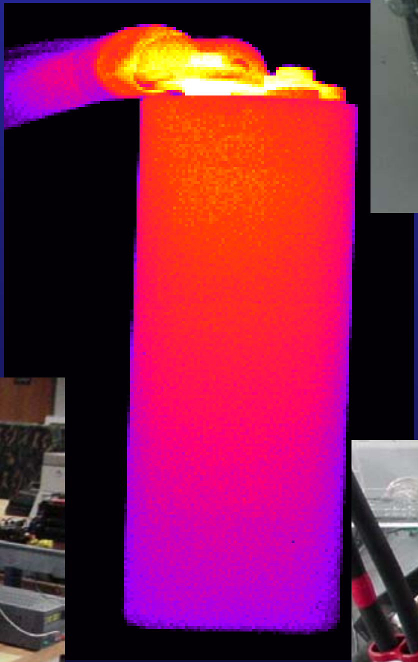
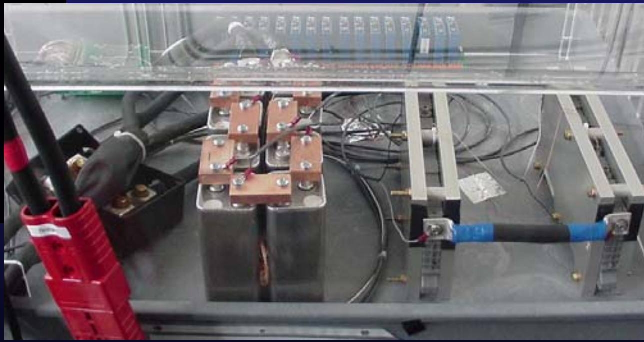


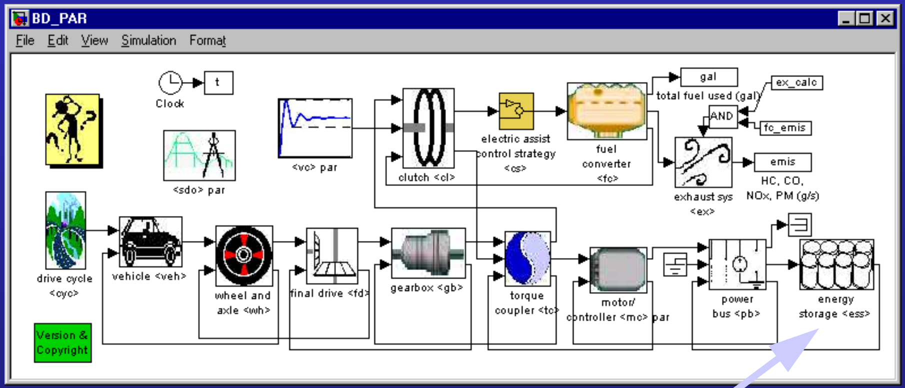


Modeling Approach

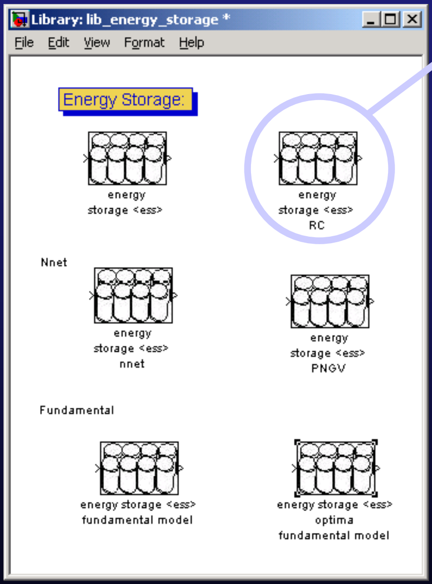
- Use established battery models in ADVISOR.
- Develop ultracapacitor model for use in ADVISOR.
- Incorporate the hybrid energy storage architecture into ADVISOR.
- Validate laboratory tests.

ADVISOR's Battery Model Selection

Block Diagram



Library



Battery Models

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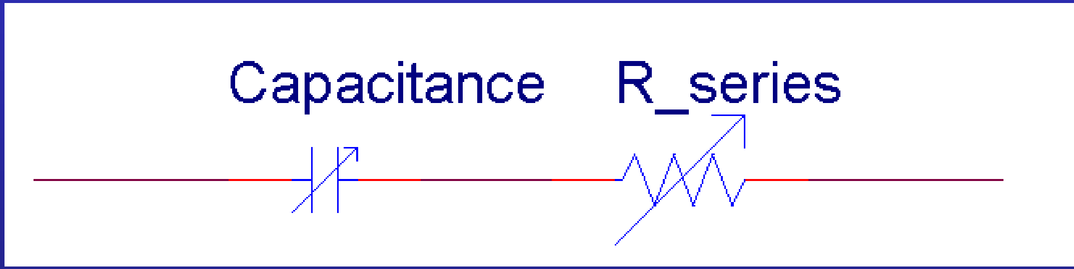
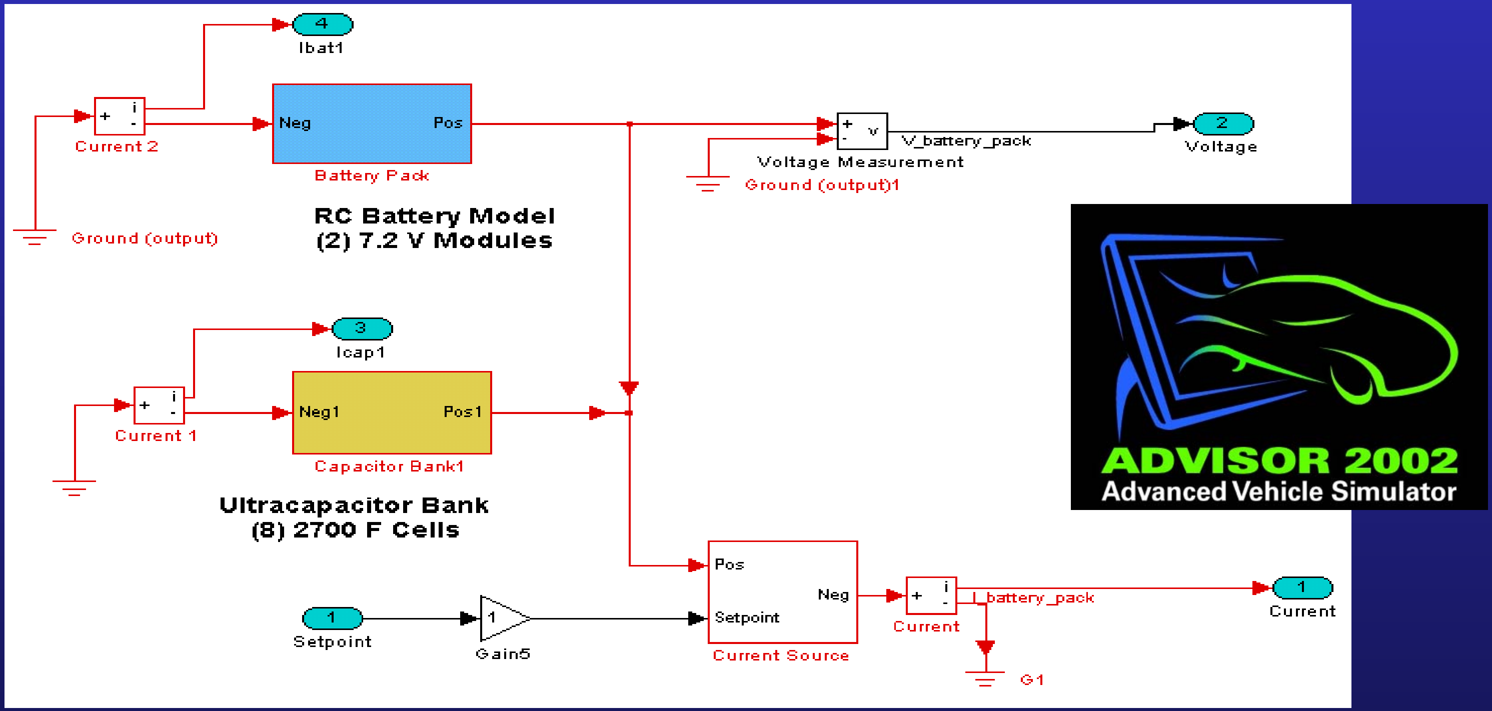
Ultracapacitor Model Development



- Capacitance and resistance vary with temperature and charge/discharge current rate.

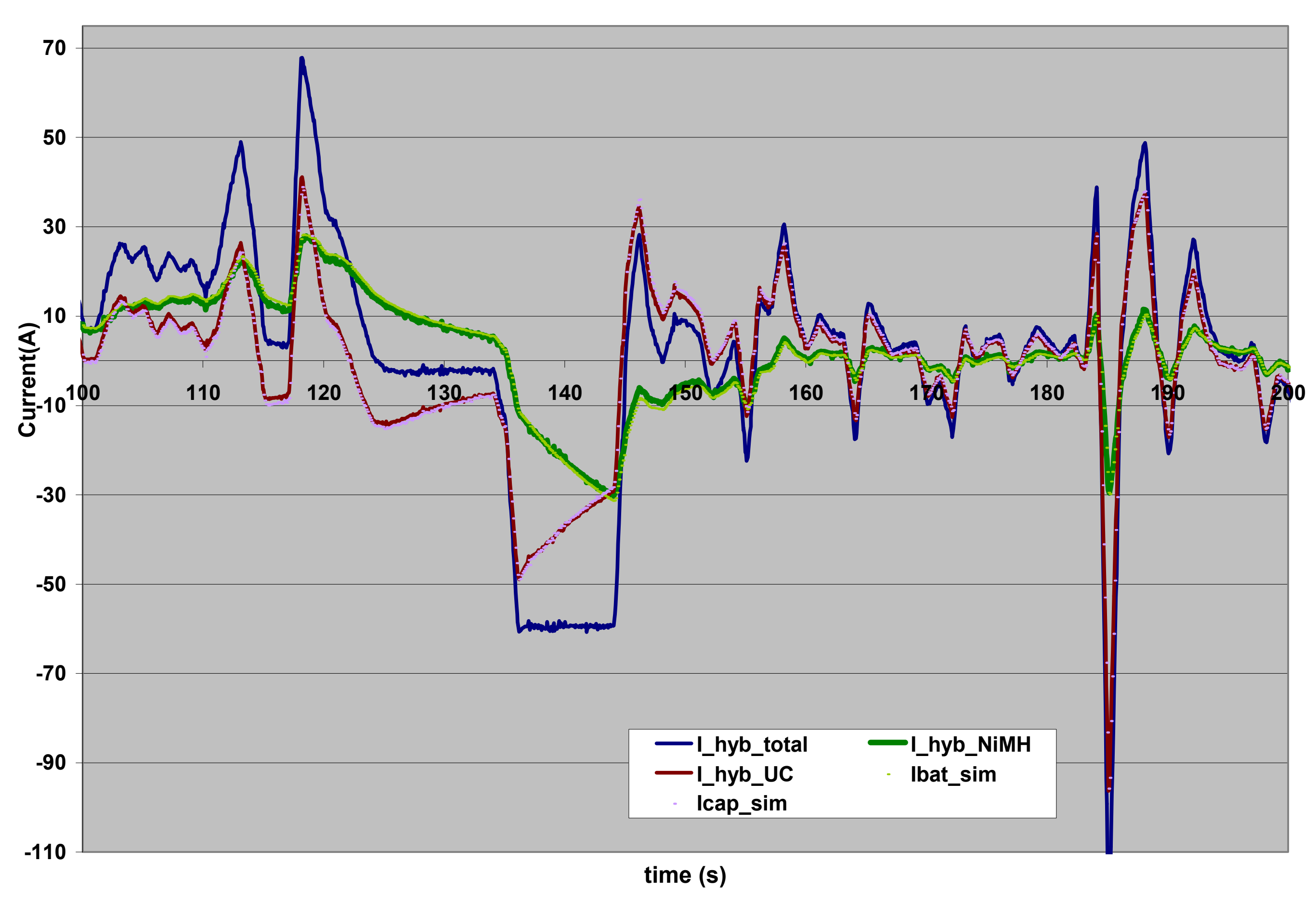
- In the model, inductance and parallel resistance are neglected because of the relatively low frequencies and the lack of sufficient “dead time” for self discharge to occur during simulations.

Modeling the Hybrid Energy Storage Setup

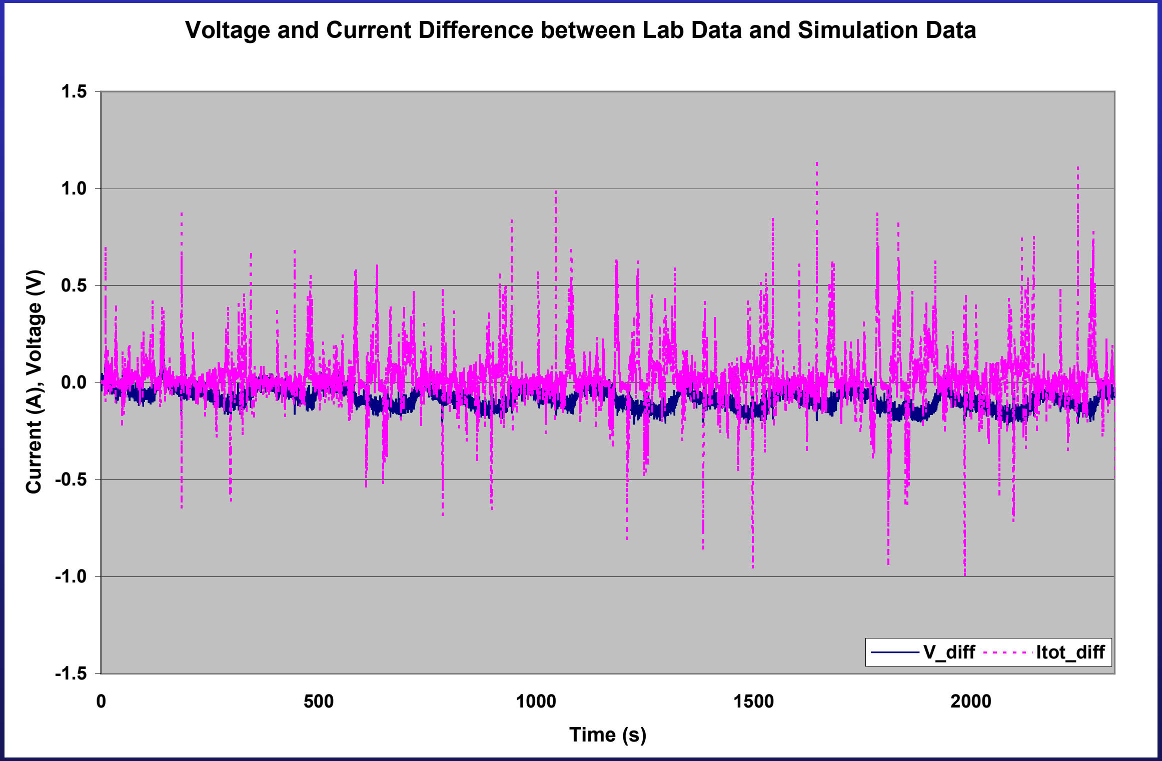


- Matlab/Simulink based model with use of SimPower Systems blockset

Simulated Current Distribution Agrees Well with Lab Data

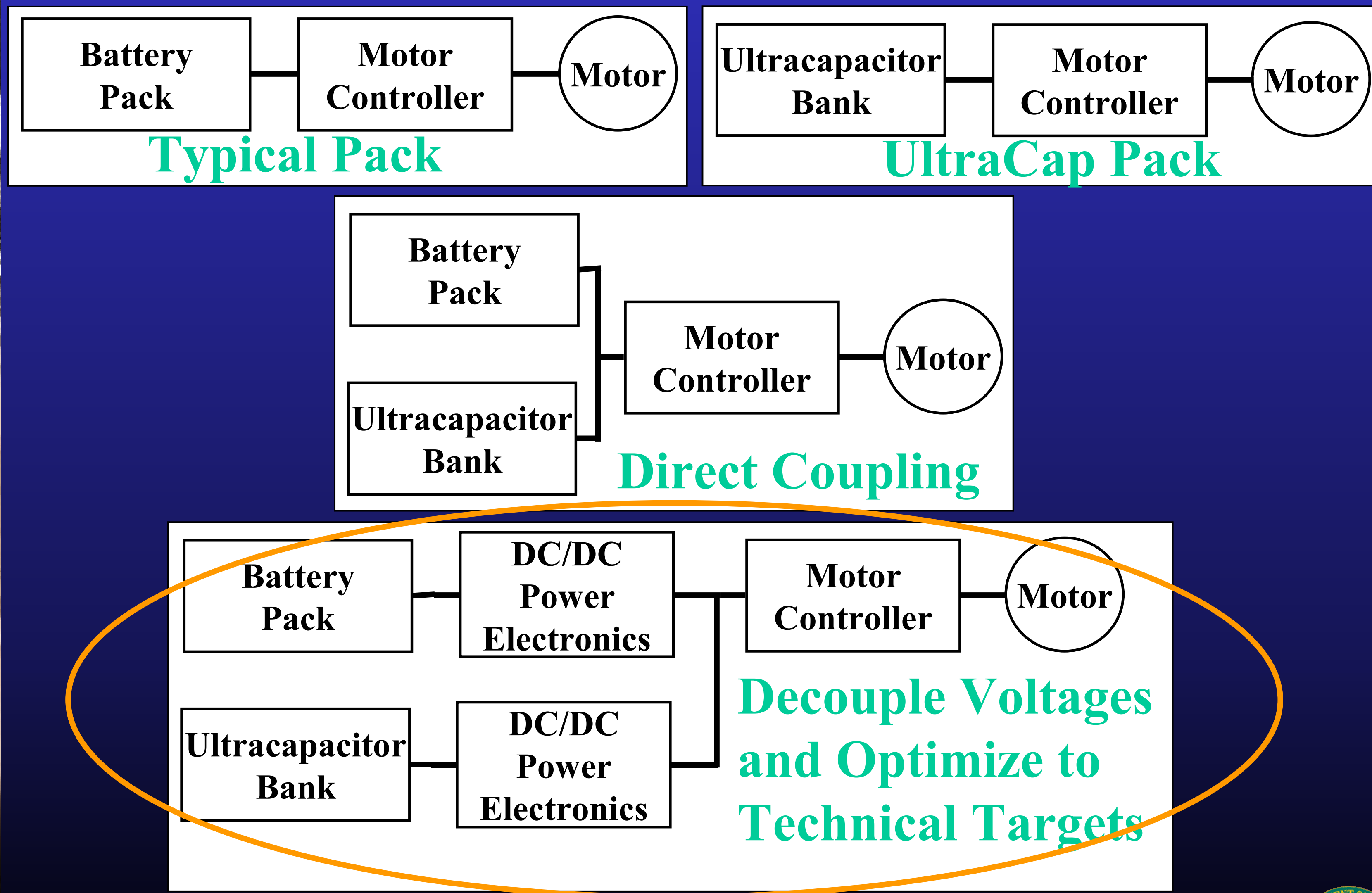


Model Validation Agrees Well with Lab Data



- Simulated voltage within ±0.25V and simulated total current within ±80mA

Software Enables Simulating Numerous Configurations



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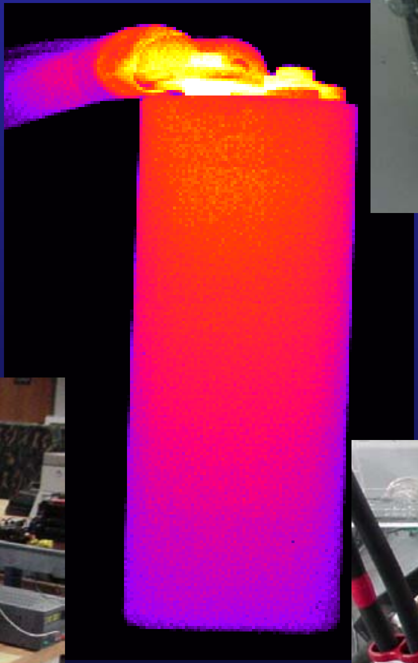
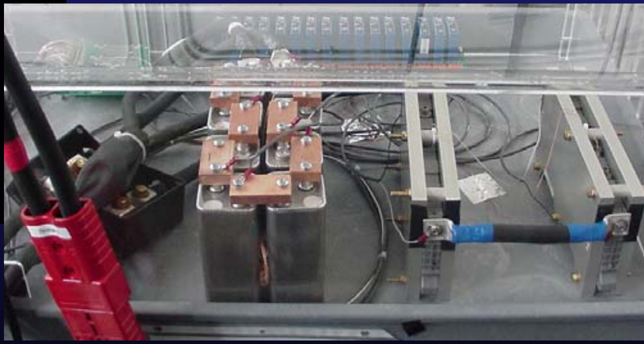
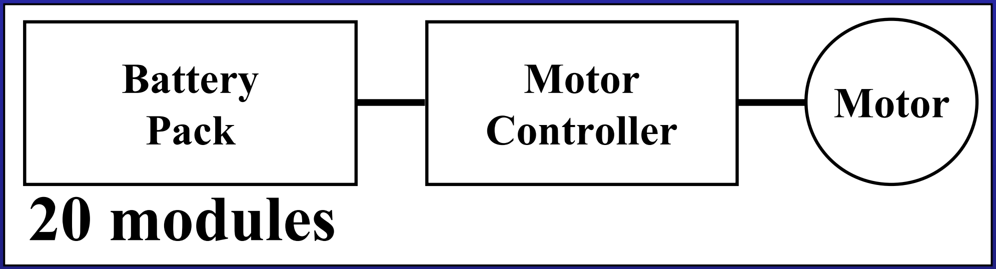




Baseline Battery Pack Configuration



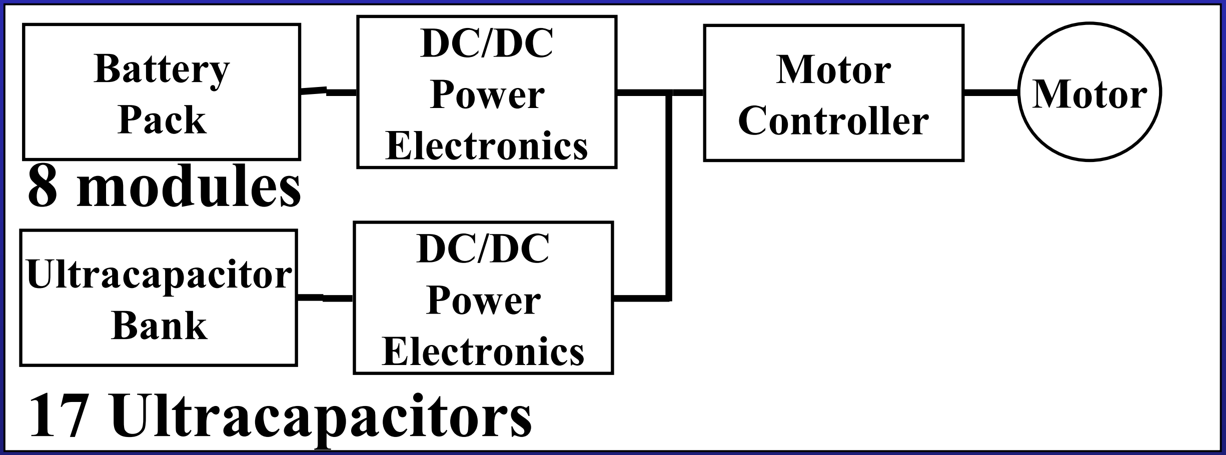
- 20 NiMH modules with 120–180V range
- Battery pack voltage range matches motor drive voltage requirements

Optimizing Component Count to Meet All Technical Targets

Characteristics	Units	Derived Insight Technical Targets
Pulse discharge power	kW	9.425 (18 s)
Peak regenerative pulse power	kW	11.375 (2 s)
Total available energy (over DOD range where power goals are met)	kWh	0.38 (at rated Ah capacity)
Specific power (based on regen power)	W/kg	426 (including enclosure weight)
Specific energy	Wh/kg	**14.2 (including enclosure weight)**
Maximum weight	kg	26.7 (including enclosure)
Maximum volume	L	15.6 (including enclosure)
Operating voltage limits (Note: Maximum current is limited to 217 A at any power level)	Vdc	max ≤440 min ≥(0.55 × Vmax)
Temperature range:		
Equipment operation	°C	Manufacturer’s rating
Equipment survival	°C	Manufacturer’s rating

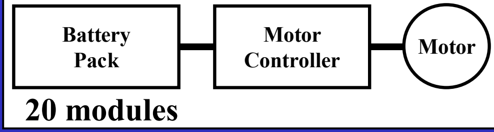
- Optimizer checks device current limits aren’t exceeded under maximum conditions.
- Battery, ultracapacitor, and power electronics costs could easily be incorporated in optimization with “accurate data.”

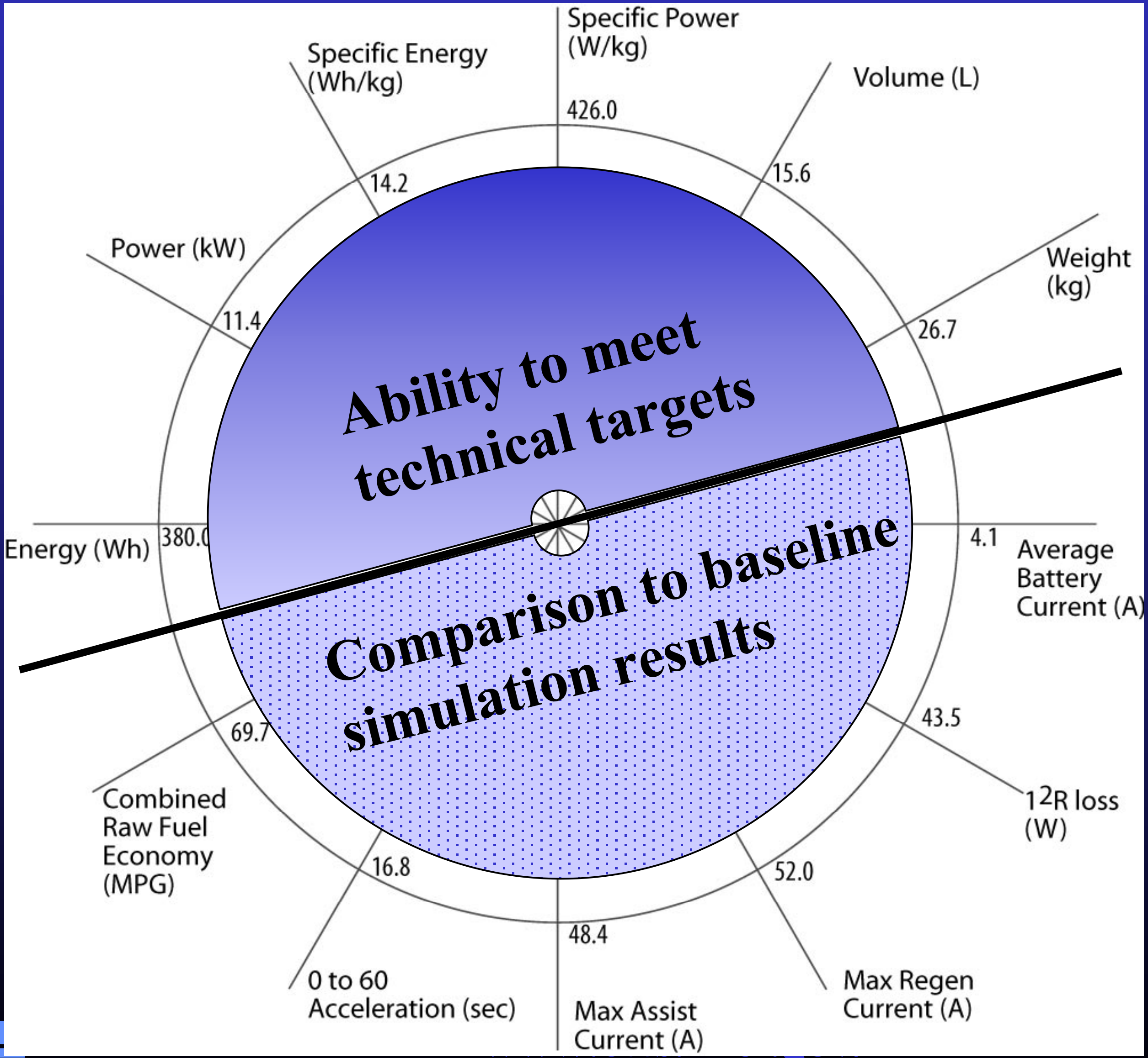
Optimized Pack Configuration



- 8 NiMH modules with 48–72V range
- 17 Ultracapacitors with 21–43V range
- Energy storage pack voltages are boosted to motor drive requirements

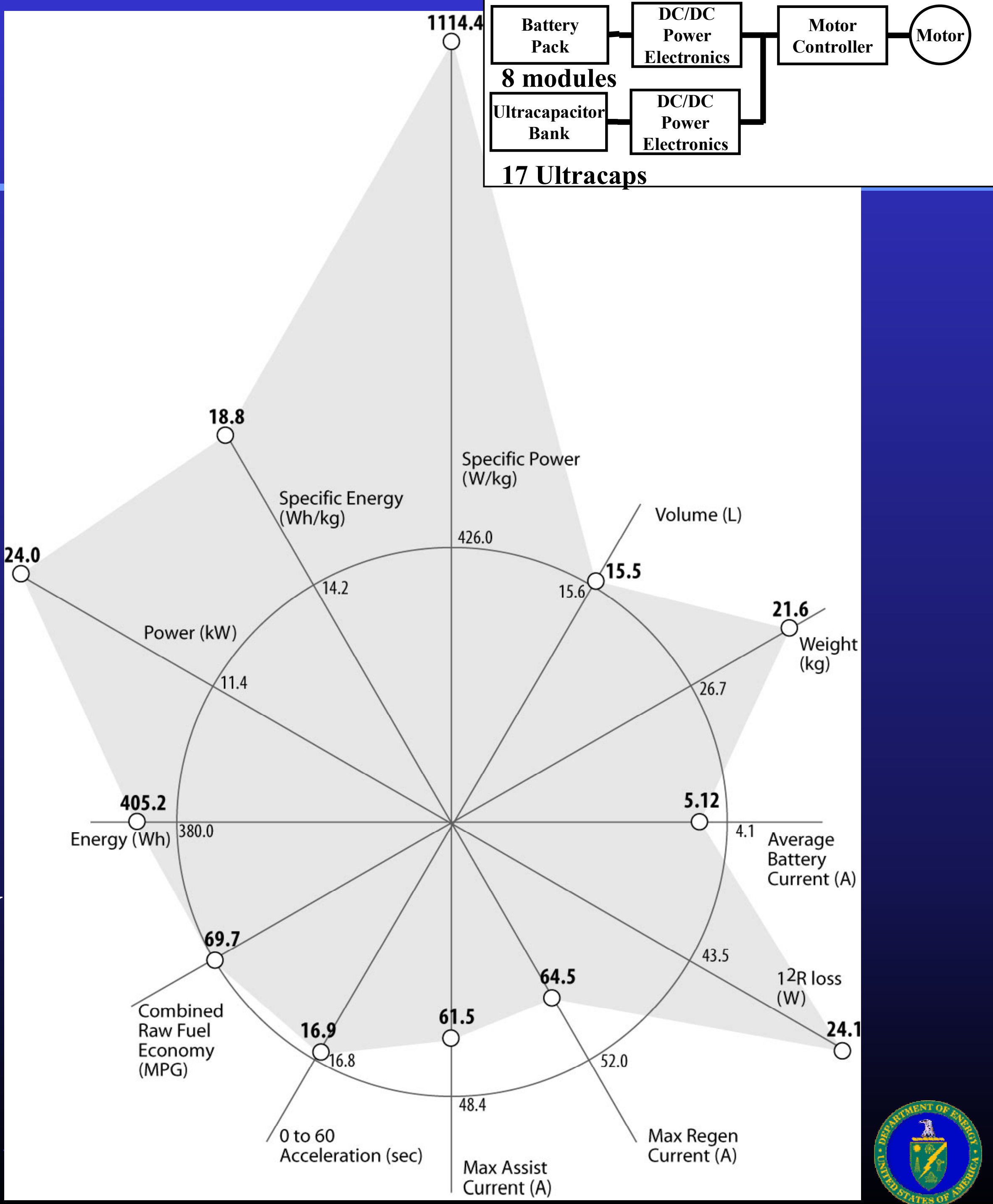
Baseline – Battery Pack





Optimized Assessment

- 8 battery modules, 17 ultracapacitors
- Expanded performance results are expected with more advanced control strategy development



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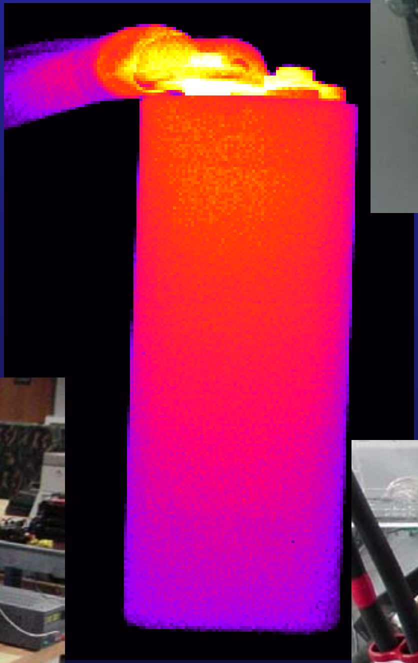
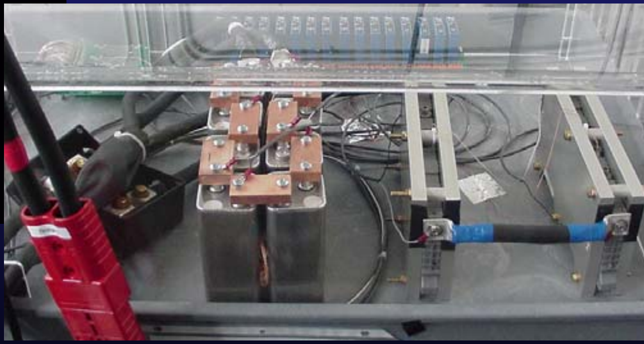
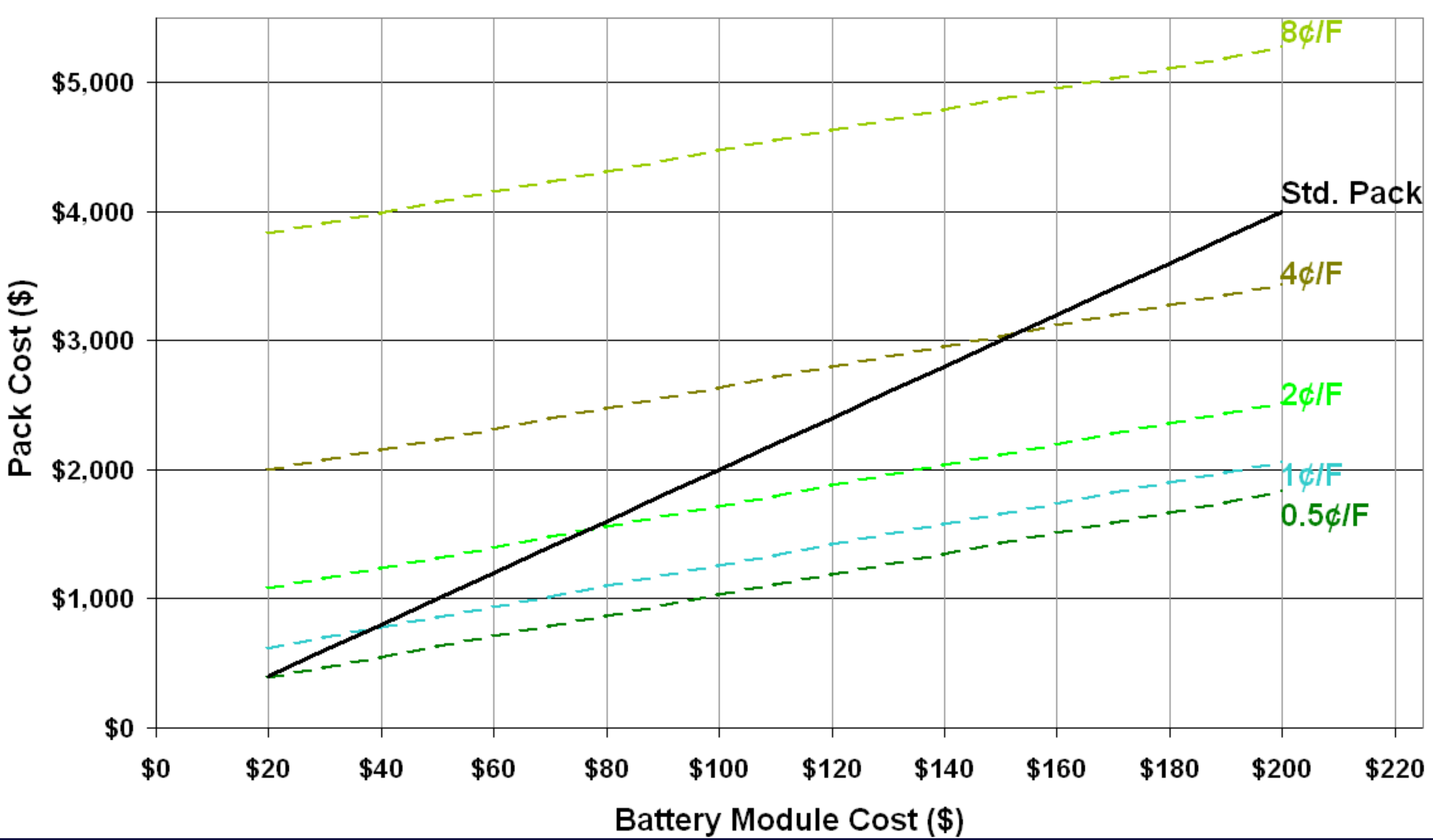


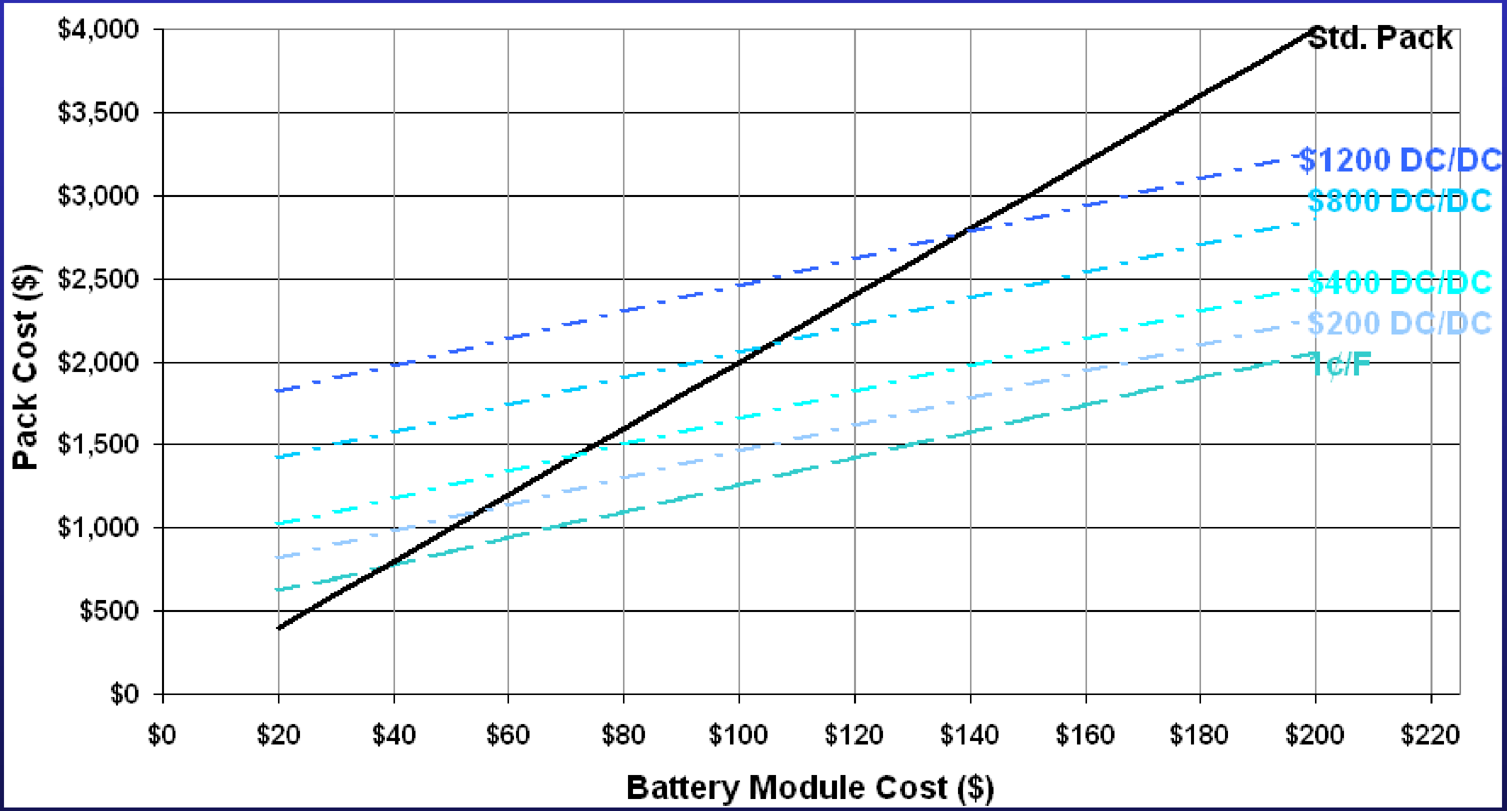


Energy Storage Cost Comparison



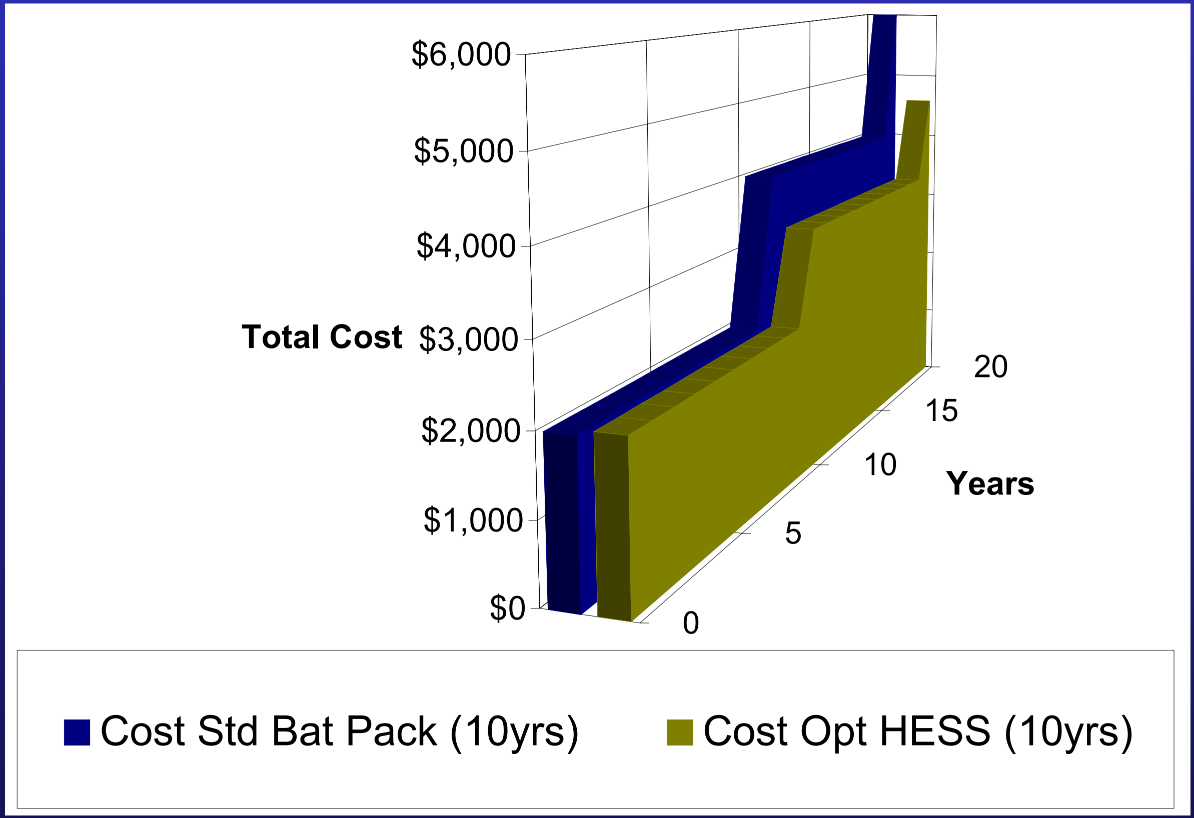
- Total pack cost for standard battery pack and optimally sized battery+ultracapacitor pack (for various ultracapacitor cost projections)

Energy Storage System Cost Comparison



- Total pack cost vs. battery module cost with converter cost lines and base ultracapacitor cost set to 1¢/F

Lifetime Cost Estimates (10 year lifetime)



- Assuming...
  - $100/ battery module
  - 1¢/F UC's
  - $800 DC/DC converters' cost

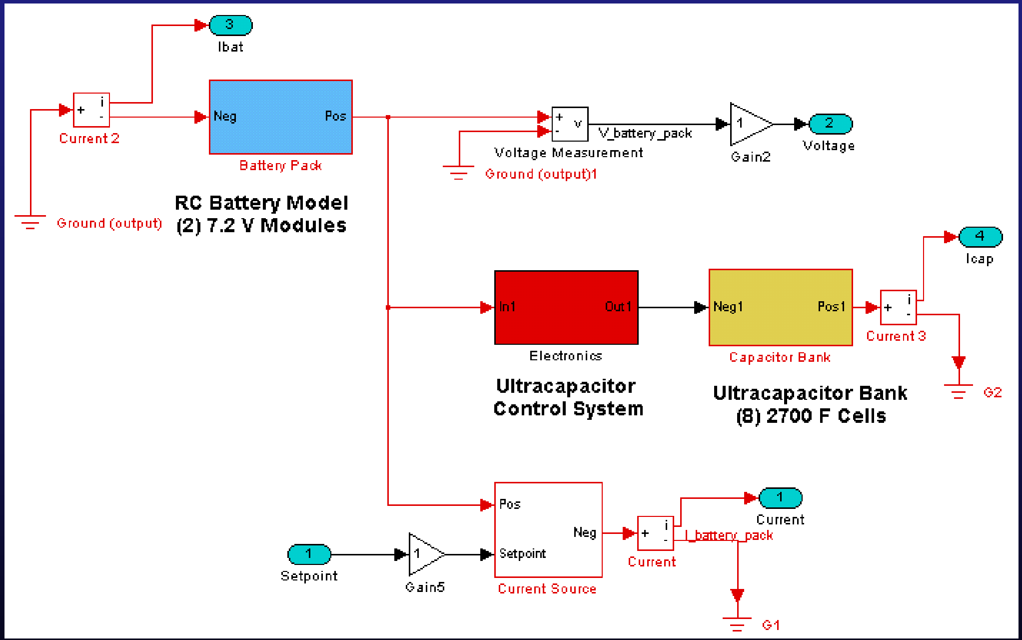
- Hybrid pack replacement costs will also be different (assuming replacement of all energy storage components simultaneously).

Conclusions

- The process to simulate, optimize, and further evaluate hybrid energy storage configurations was developed.
- Hybrid energy storage does have potential for satisfying technical and financial targets.
- First-run battery + ultracapacitor control strategies have maintained vehicle performance.

Future Work

- Improving the hybrid energy controller should improve mileage, performance, etc…
- Verifying an optimized configuration through laboratory testing is important.
- Further cost/life data are needed.



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Tony Markel, Vehicle System Analysis Team

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And for ADVISOR downloads,…

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